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Project Title: Grounding Zone and Tidal Response of the Amery Ice Shelf, East Antarctica

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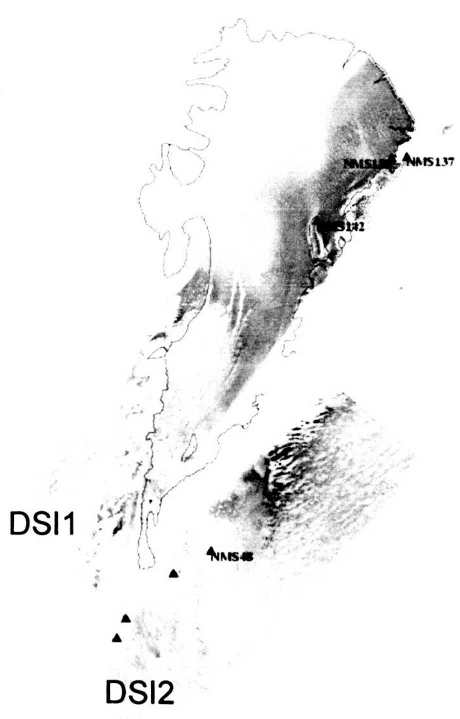
This report summarizes the main findings of the research project. Unfortunately, it turned out that there was not a great deal of SAR data over the Amery Ice Shelf that we were able to work with on the project; nevertheless, we did make considerable progress on this project, with both the existing SAR data and new field measurements that were collected under this grant. In total we had constructed two SAR interferograms (SSIs), and four SSIs. The latter were combined them to construct two differential SAR interferograms (DSIs; Figure 1). DSIs are useful because the contribution to the SAR phase from horizontal ice motion is eliminated, since the time difference between the first and second pass within both image pairs used to make the DSI is the same for each pair. The SSIs and DSIs have revealed several interesting glaciological features, and have added to our knowledge of the Amery Ice Shelf (AIS).

After constructing the two DSIs we undertook the following steps:



1) ***Image geolocation*** we geolocated the DSIs using control points, identified on the SAR amplitude imagery by comparison with AUSLIG maps and aerial photographs. The red triangles on the mosaic show the control points used for each swath. Once offsets in range and azimuth of the SAR images (due to factors such as squint angle and clock errors) were found, swaths were geolocated by synthetically flying the satellites along their precise orbits (from Delft University).

2) ***Removal of topography*** we corrected for the effect of topography on the phase (due to slightly different viewing geometry) over the floating ice using a 1-km Digital Elevation Model for the Amery Ice Shelf, made from ERS radar altimeter data (*Fricker and others, 2000*).

E1-23982	E2-04309	E1-24483	E2-04810	DSI1
15 Feb 96	16 Feb 96	21 Mar 96	22 Mar 96	
Baseline 153 m		Baseline 269 m		
E1-23810	E2-04137	E1-24311	E2-04638	DSI2
3 Feb 96	4 Feb 96	9 Mar 96	10 Mar 96	
Baseline 230 m		Baseline 168 m		

Figure 1 *Mosaic of SAR swaths along orbits for which we had two sets of tandem pairs, and have constructed differential SAR interferograms (DSIs). DSIs were each made from two single SAR interferograms. The orbit numbers and dates for the passes used for each SSI are shown in the table. The details for the eastern (leftmost) swath are presented first.*

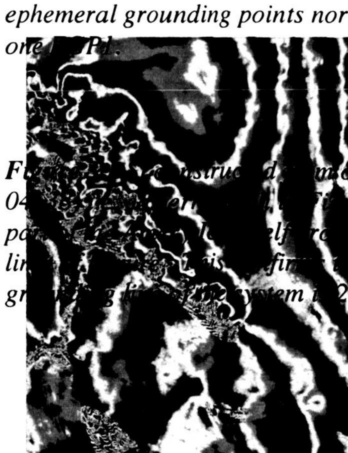
The DSIs made from the swaths shown in Figure 1 are presented in Figures 2 and 3. Over the floating ice the major contributor to the phase difference observed in these DSIs is due to vertical displacement of the ice shelf (due to tide action and inverse barometer effect). Other minor contributors are due to orbit errors and atmospheric correction errors.

The DSIs have allowed mapping of 50% of the grounding line of the ice shelf and also enabled us to identify several "ephemeral grounding points" (*Schmeltz and others 2001*):☒

Grounding line mapping: The grounding zone is apparent in the DSIs as it corresponds to the closely-spaced fringes bordering the floating ice, where the ice is neither fully-floating nor fully-grounded. We digitised both the fringe that corresponds to the landward or outer edge of the grounding zone, and that which corresponds to the seaward edge. The outer edge represents the limit of ice flexure, which we call the grounding line.

The InSAR-derived grounding line from the two DSIs is shown in Figure 4, along with previous grounding lines from other sources.☒ The blue dots are the grounding line inferred from Landsat 4/5 TM imagery (provided by Neal Young); the red line is grounding line defined using from hydrostatic calculations with ERS radar altimeter (RA) data and airborne radio-echo sounding data (Fricker et al 2002); the black line is grounding line from InSAR. RA data in the south part of the ice shelf are sparse due to rougher topography encountered, so the differences in GZ location there are in the order of 10 km.

Figure 2 *DSI constructed from orbits (E1-23982 – E2-04309) – (E1-24483 – E2-04810) i.e. western swath in Figure 1. Note a slight discontinuity in phase where we joined two portions of the swath together, plus phase anomaly due to a missing line in the data files from ASF. Solid line on left is the limit of flexure, dashed line is the seaward edge of the flexural boundary layer. Inset shows two ephemeral grounding points north of Gillock Island. We name the westernmost on[illegible]P1.*

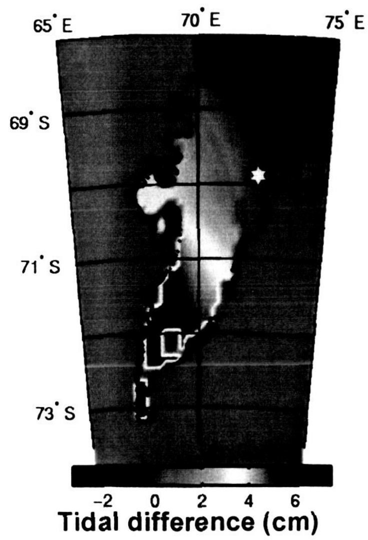


F[illegible]rbits (E1-23810 – E2-04137) – (E1-24311 – E2-04[illegible]re 1. This area just captures the southernmost p[illegible]ding line, and the dashed line indicates the li[illegible]e findings of Fricker and others (2002) that the g[illegible]00 km than had previously been reported.

InSAR defines grounding line more faithfully than hydrostatic calculations or image analysis. In the southern AIS the line from InSAR is close the break in slope visible in the images.

Ephemeral grounding points: There are several ephemeral grounding points (EGPs) on the ice shelf. These are points that are floating at some parts of the tidal cycle and grounded during others. We looked closely at on one such point (EGP1 in Figure 2), and found that it is actually only grounded for a small portion of the tidal cycle, hence we were very fortunate to observe it. EGPs are useful as indicators of changing ice thickness in the system, since if the ice becomes thicker the point will be grounded for a greater fraction of the tidal circle, and vice versa.

Contributions to observed vertical displacement



We assumed that most of the vertical displacement observed in the long swath interferogram (Figure 2) was due to differences in tidal amplitudes between the four SAR passes contributing to the DSI. We computed the tidal differences for those pass times from the CATS model (*Padman and others, 2001*), shown in Figure 5 for the whole ice shelf. The differences range from –3 cm in the southeastern part of the shelf to +6 cm to the northeast. These are very small differences, typical differences in DSI on ice shelves usually being on the order of 10s of cm (Marjorie Schmeltz, *pers. comm.* 2002).

Figure 5. *Difference in tidal amplitudes between SAR passes of long swath DSI (h_1-h_2-h_3+h_4) computed from Laurie Padman's CATS model. Note that the difference is much larger in the southern portion of the ice shelf, and that it changes sign between the north-eastern and the south-western parts of the ice shelf.*

There are four fringes corresponding to the grounding line in the north-eastern section of the ice shelf, which amounts to -11.2 cm of total displacement in the direction of the SAR (each fringe represents -2.8 cm). However, from Figure 3 we see that there tidal difference was only around –2 cm. Therefore some other effect must be dominating the vertical displacement. We propose that this other effect is that of pressure *i.e.* the "inverse barometer effect (IBE)".

We looked at pressure data from nearby Automatic Weather Stations to see if this could be possible. There is a large network of AWS in the Lambert Glacier Basin (LGB) system, several of which have been operating for almost a decade, high up on the plateau around 2000 m elevation (named LGBxx). Unfortunately AWS were not installed on the Amery Ice Shelf itself until 1999, which was 3 years after the SAR data were collected.

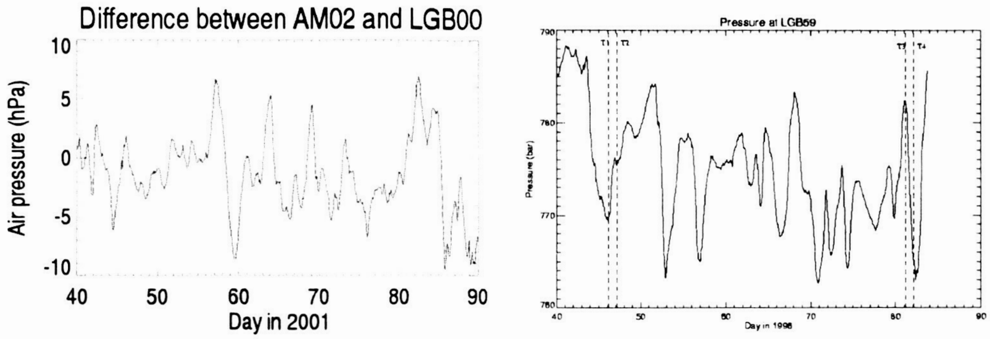


Figure 6 Left plot: Differences in atmospheric pressure for AWS on the Amery Ice Shelf (AM02) and in the Lambert Glacier Basin (LGB00) for the overlapping time period 2001. Right plot: Pressure at LGB00 coinciding with the time period of the DSI.

Figure 6 (left plot) shows that the pressure differences between LGB00 and AM02 (on the ice shelf) in 2001 can be large, so that LGB00 does not realistically represent conditions on the ice shelf. Cross-correlation analysis of the data showed that although the magnitudes of the pressure events were approximately the same, the LGB can lead or lag the AIS by up to 0.5 days. The right plot shows the record from LGB00 for the time period of the DSI. The vertical bars represent the four times of the SAR passes. It can be seen that changes in pressure on the order of 8 hPa (necessary to create a -8 cm displacement) could easily have occurred on the ice shelf during this time period. Therefore atmospheric pressure could be accounting for most of the displacement seen in the DSI, so it is a rare visualization of the IBE on an ice shelf.

Note that there are only two fringes in the grounding zone of in the south-western section of the long swath interferogram in Figure 2. The difference in the number of fringes between the northeast and southwest is due to the difference in the tidal amplitudes in different parts of the ice shelf (Figure 5).

We examined further the state of the tide during the four SAR passes for the DSI, and were surprised to find that the tide was very low during all four passes (Figure 7). This is really unusual. The tide height was -44.1 cm at t_1, -45 cm at t_2, -46.4 cm at t_3 and -47.9 cm at t_4. We examined the two SSIs that made up the DSI, and saw that EGP1 was visible in first interferogram of DSI (t_1-t_2), but not in the second (t_3-t_4; see panel to right), even though tidal amplitudes were lower at t_3 and t_4, so there must have been higher atmospheric pressure at either t_1 or t_2.

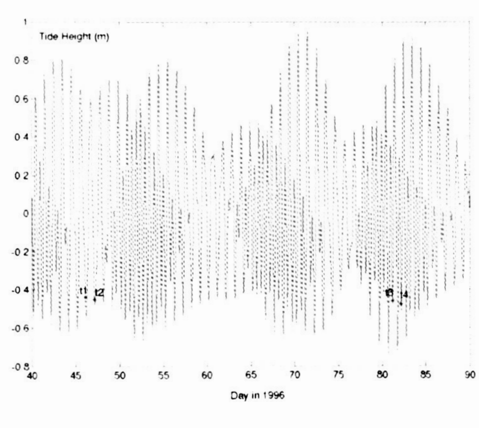


Figure 7 Computed tidal heights for the time period of the DSI, indicating the tidal state for each of the SAR passes (t_i is the time of the i^{th} pass).

Another explanation for observing EGP1 in the first interferogram and not the second is that the ice thickness changes between one time frame and the next. EGP1 lies downstream of a crevasses initiation zone, and so the ice thickness could definitely be changing along that flowline. It is possible that a slightly thinner piece of ice was advected to the EGP1 location between t_2 and t_3, such that there was no longer a point of contact.

We can make an approximate estimate of the water column thickness in the cavity below EGP1 from these SAR results. One fringe surrounds EGP1 in DSI, corresponding to 2.8 cm of displacement in direction of radar. The water column thickness beneath EGP1 is $\simeq$50 cm at equilibrium tide, therefore EGP1 is probably only grounded for 5-10% of the tidal cycle, so we were fortunate to observe it.

The work presented above was presented in the form of a poster at the Fall 2002 AGU meeting "InSAR-derived grounding features of the Amery Ice Shelf, East Antarctica", by Helen A Fricker, Jeremy Bassis, Karen Chadwick and Laurie Padman see http://rai.ucsd.edu/~helen/AGU_2002/AGU_Poster_2002_smaller.ppt

A paper describing the Amery Ice Shelf rift system and its significance was presented at the IGS conference in June 2001 and published in Annals of Glaciology 34 (*Fricker et al.*, 2001). This paper included InSAR results obtained during this project.

Amery Ice shelf fieldwork 2002-2003

A more complete understanding of the origin and evolution of the features observed in the InSAR data required combination high spatial resolution of SAR with a measurement with a higher temporal sampling rate. In order to do this, we designed a field experiment to deploy GPS instruments on the features to monitor their evolution. Within this context, we took an opportunity to take part in an Australian National Antarctic Research Expeditions (ANARE) field project to the Amery Ice Shelf (2002-3). The necessary logistics were provided through the Australian Antarctic Program (AAP) at a cost of approximately $A0.6-8M through a successful proposal submitted in July 2001 with Richard Coleman of the University of Tasmania as Principal Investigator and Helen Amanda Fricker and Neal Young as co-investigators. Jeremy Bassis, an IGPP graduate student working on this project, went to Antarctica in November 2002 with Richard Coleman. They had a very successful field season, which resulted in some new information about the ice shelf rift propagation process, a fundamental process in glaciology.

"Loose tooth" rift system

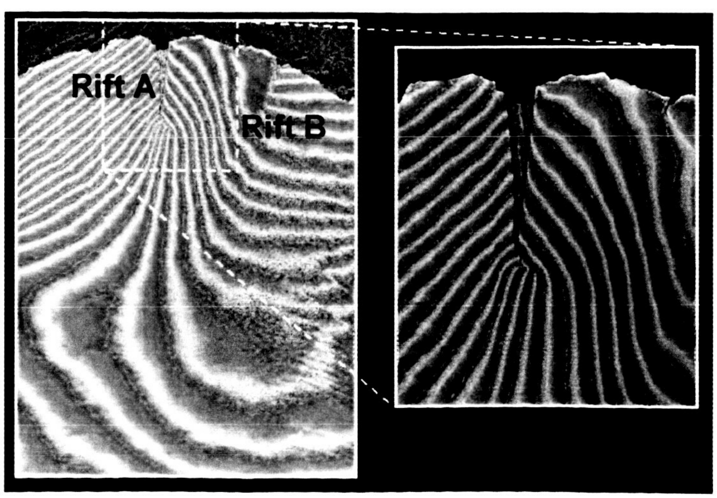


Figure 8. Interferogram derived from ERS-1 orbit 24526 (3/15/1996) and ERS-2 orbit 04309 (3/16/1996) of the eastern part of the Amery Ice Shelf front.

Figure 8 shows an interferogram generated from ERS tandem data from repeats along a descending track, which passed over the central Amery Ice Shelf front. The interferogram contains relative displacement information arising from ice flow (topography has been removed, and the differential tide was only a few mm). There are discontinuities in the phase across each of rifts A and B, and across the transverse (perpendicular-to-flow) fracture just beginning to form at the tip of Rift A. The fringes across the ice between the rifts are orientated differently to that outside the rifts. We suggest that this is because the "loose tooth" is moving in a different manner to the rest of the ice shelf, as a result of the spreading of the fracture at its southwest corner.

We saw the "loose tooth" rift system as a timely opportunity to investigate the forces controlling ice shelf fracture and rift formation, leading up to an iceberg calving event on the Amery Ice Shelf. We monitored the rift system with an array of GPS receivers and seismometers to measure the propagation (widening, elongation and vertical displacement) of the rift. Reconnaissance of the rift took place on 7th December, and six instruments were deployed on the ice shelf between December 8th and January 26th. Figure 9 shows a photograph of the rift taken during reconnaissance, and one of the rift stations. Figure 10 shows the network of GPS/seismometer sites that were deployed around the rift tip. In addition, radio-echo sounding (RES) flights were made over the "loose tooth" in late November 2002, using a new RES system on board a Twin Otter.

The fieldwork led to the discovery of episodic behavior in rift propagation. From analysis of the 2002-3 field data, we observed three discrete events where swarms of seismicity were accompanied by sudden rift widening (Figure 11). Furthermore, it was shown that the propagation events were not related to environmental factors such as wind speed and tides. This significant result was published in a recent paper in Geophysical Research Letters:

BASSIS, J.N., R. COLEMAN, **H.A FRICKER** and J-B MINSTER (2005), Episodic propagation of a rift on the Amery Ice Shelf, East Antarctica, *Geophysical Research Letters, Geophysical Research Letters*, 32, L06502, 10.1029/2004GL022048.

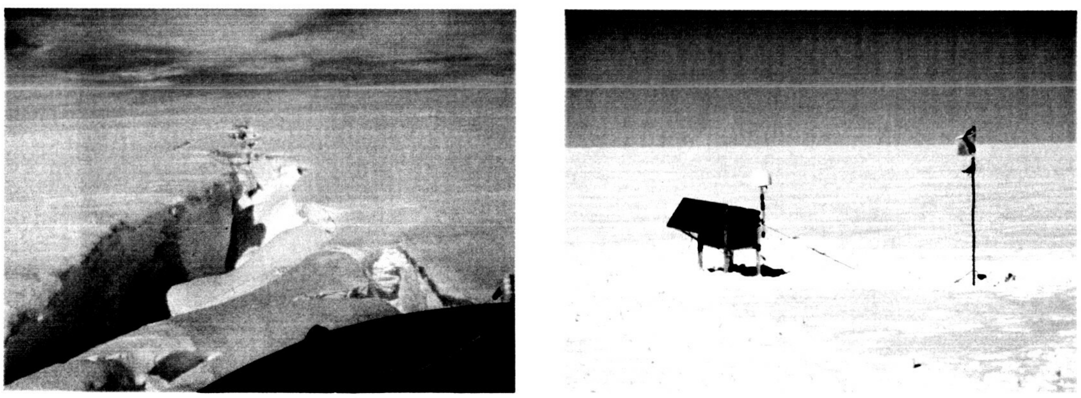


Figure 9. *Left: transverse crack taken from helicopter during reconnaissance survey December 7th 2002. Right: GPS setup at one of the "loose tooth: sites. Photographs taken by Richard Coleman, University of Tasmania.*

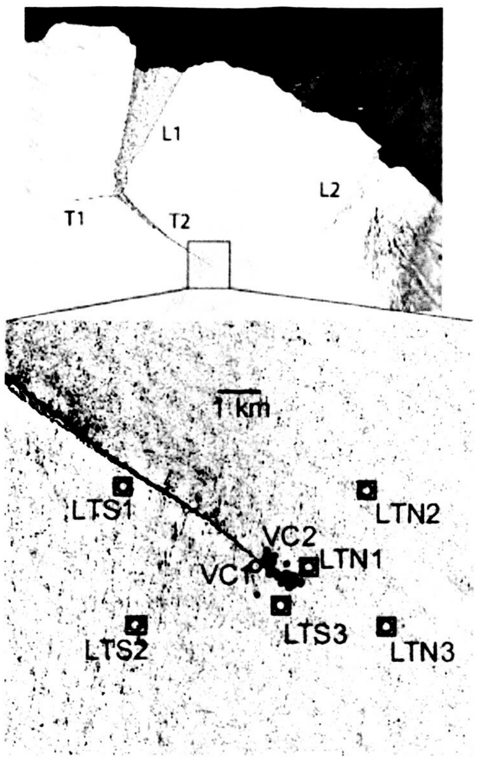


Figure 10. *Network of GPS/seismometer stations installed on the Amery Ice Shelf from December 8 2002 to January 26 2003, overlaid on Landsat 7 image. Seismometers are plotted as circles, GPS are squares. Epicenters of seismic events are shown as blue dots. From Bassis et al, 2005).*

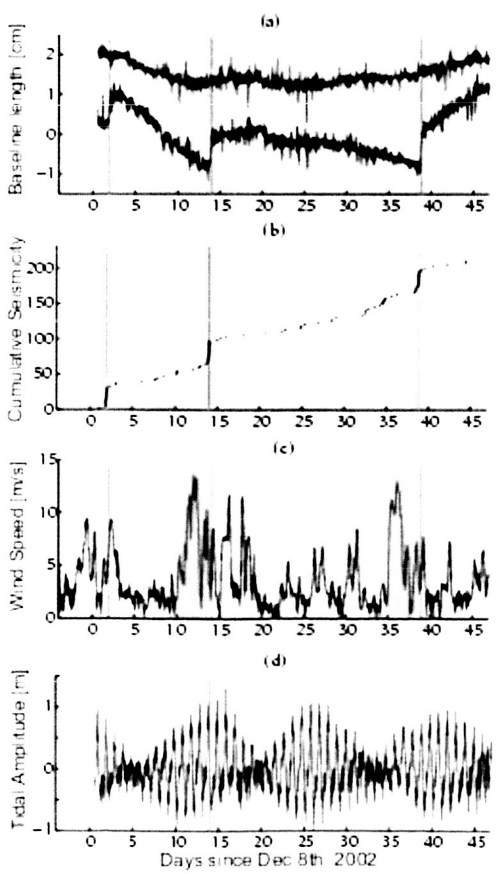


Figure 11. *a) Detrended time series of GPS baseline lengths, normal-ro-rift component is blue line. Parallel to rift component is vertically offset and shown in red b) Cumulative seismicity at LTN1 c) wind speeds from Automatic weather stations. Two of the three bursts of propagation were preceded by periods of high winds (shaded region) d) one hour tidal amplitudes for LTS3 obtained by processing the GPS data relative to fixed rock sites, green lines show time of the three propagation bursts.*

Multi-year propagation: A second major result from studying this rift system, with SAR imagery and other satellite imagery was the discovery of a seasonal pattern in rift propagation rates: From analysis of an eight-year time series of satellite image data, we have found that rifts grow faster in the summer than in the winter (Figure 12). This is the first time this seasonal signal has been observed in ice shelf rifting. We submitted a paper reporting this result to GRL in July 2004, which was published January 21st 2005, in parallel with another paper on ice shelf rifting by our colleagues Ian Joughin and Doug MacAyeal. The seasonal pattern was supported by GLAS data which show widening of one of the rifts in the summer but not in the winter (this was presented at the Fall AGU 2004). The reference for the GRL paper is:

FRICKER, H.A., N.W. YOUNG, R. COLEMAN, J.N. BASSIS and J-B. MINSTER (2005), Multi-year monitoring of rift propagation on Amery Ice Shelf, East Antarctica, *Geophysical Research Letters*, 32, L02502, 10.1029/2004GL021036.

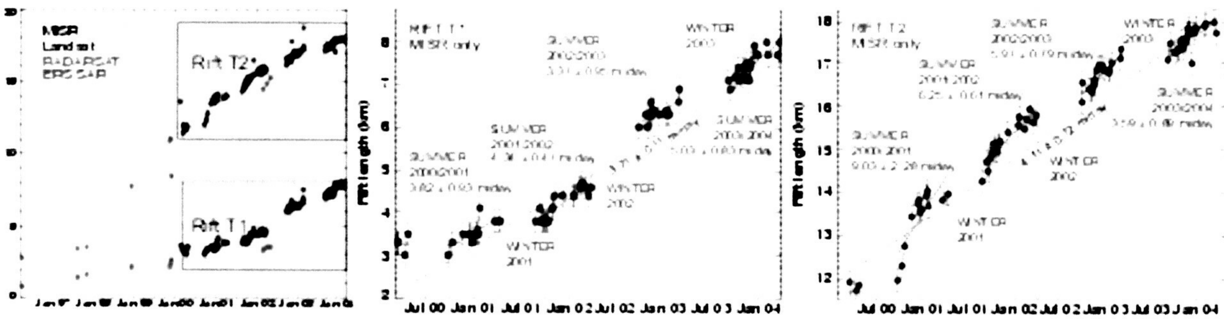


Figure 12a) Measured rift lengths derived from satellite imagery from 1996 to present. For each image type, the error bars represent 1 pixel, where the pixel sizes are: ETM = 12.5 m; ERS SAR = 100 m; RADARSAT = 200 m; MISR = 275 m. Center/right panels: MISR time series for T1 and T2, showing results of regression analysis given in Table 1 (red solid lines are Case A and black dashed line is Case C). From Fricker and others 2005.

Flexural boundary layer/ephemeral grounding point

The second component of the 2002-3 fieldwork focussed just north of Gillock Island region, in a region of the grounding zone that is separate from the eastern margin (Figure 11). This work will take place from about December 22nd, subject to clear flying weather from Davis station, Antarctica. Four profiles will be surveyed, Profile 1 (Gill1_1, to Gill1_4) crosses EGP1, Profile 2 (Gill2_1, to Gill2_4) crosses the northern flexural boundary layer, Profile 3 (Gill3_1, to Gill3_4) crosses the southern flexural boundary layer. At each site, a GPS receiver was placed for at least 24 hours i.e. for a complete tidal cycle. In November 2002 a Twin Otter carrying a new RES system also collected data over these features. The combination of GPS and RES\ will give us detailed measurements to help understand the nature of the ice shelf response to tide in the flexural boundary layer. Additionally it will also enable us to investigate the tidal response at EGP1 and learn more about that feature.

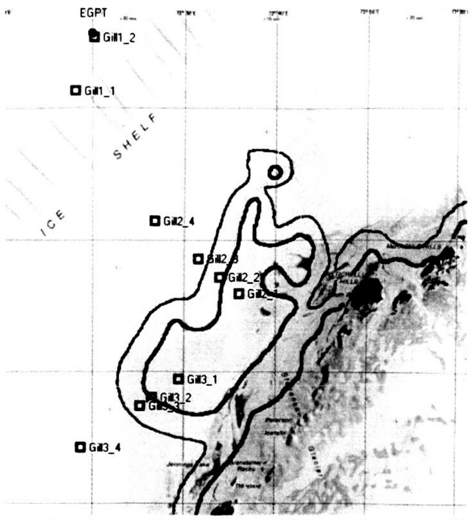


Figure 13. Survey plan for second component of 2002-2003 season fieldwork on the Amery ice shelf. The blue line is the limit of flexure (i.e. the grounding line), traced from the InSAR. The red line is the seaward boundary of the flexural boundary layer, or grounding zone, also from InSAR. The area in between the red and blue lines is the flexural boundary layer. Sites Gill1_1 etc are GPS sites to be occupied by static GPS.

The data from this part of the fieldwork are still being analyzed, but the GPS data across the grounding zone show evidence of the ice shelf responding fully hydrostatically to tides at Gill1_4 and Gill2_4 (the seaward sites), not responding at all at Gill1_1 and Gill2_1 (the landward sites) and displaying damped tidal behavior at the sites in between. We are working on a publication with Richard Coleman on this subject. The results of the GPS survey at the ephemeral grounding point do not show any evidence of grounding at this point, confirming that our observation of this effect in the InSAR data was extremely serendipitous.

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